Low Pressure Greenhouse Concepts for Mars

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Abstract

A project was initiated to begin testing some environmental limits for managing plant growth systems. These limits will help determine some of the concepts for building plant enclosures for use on Mars. In particular, the study focuses on the effects of reduced atmospheric pressures. Structural design is considered as it relates to the biological processes that would occur within that structure. The design must be closely tied to the functionality of the biological system and has a few primary concerns that need to be tested to resolve the question as to the path of design. Early test indicate that plants can survive and grow at low (>76 mb) pressure.

Background

The Martian surface is a cold (-143°C to 17°C), dry environment with a very low-pressure atmosphere (7 to 9 mb). The gas makeup of the atmosphere consist of 95.3% CO_2, 2.7% N, 1.6% Ar, 0.13% O_2, and traces of other gases (McKay, 1984). There is no evidence of any surface water, but water in the form of ice may exist as subsurface permafrost (Levin and Levin, 1999). Solar radiation from the sun has a mean of 590 W m^{-2} with much higher levels of ultra-violet wavelengths reaching the surface (McKay, 1984).

In order to grow plants on the surface of Mars some protective structure must be provided to maintain a viable environment. Some concerns for such structures are: they must be able to maintain temperatures of ~15°C to 30°C, provide light at a level that will promote growth, maintain an atmosphere with the proper gas mix and pressure, and have a low mass and sufficient volume. Mass and volume are directly related to structure design and influenced by the previous concerns. In order to achieve the best mass/volume combination it is necessary to determine the lowest pressure, light, and temperature range that will grow plants efficiently.

The project does not consider the actual design of such structures but relies on design concepts to influence how plants will react to a given environment based on structure design. The crossover of structural design and plant environment can be seen when one considers the issue of transparency of the structure. If the structure is transparent and allows sunlight to be used as the primary energy input, then the level of light available to the plant must be adequate for viable growth. This becomes complicated because lightweight transparent films do not insulate well enough to maintain an acceptable growing temperature. Another consideration of lightweight films is the amount of structural stress that they can withstand. This is determined by the minimum inside pressure of the structure that is required to grow plants. The lowest pressure that plants will tolerate and still grow efficiently is not known. In addition, some plants require a relatively large volume, which means the structural stress will increase with volume. As the structure grows in size the total stress on the structure increases to a point beyond the ability of the transparent thin films limits, without adequate structural reinforcement. If more

reinforcement is added the transparency is reduced and a point of diminishing returns is reached. Design and development of transparent, high-strength, and high r-value thins films is needed to help further research for Mars greenhouse structural design. Because there is no definitive answer as to plant minimum requirements for growth it is not possible to design a structure at this time that will meet all the criteria required. Other options include opaque structures with electric or concentrated solar lighting. These structures allow for better thermal control and higher strength capabilities with some increase in mass cost. If the structure is opaque then it is possible to make it large enough to be human rated from a mobility standpoint and perhaps from an atmospheric one as well. The ability to maintain a low pressure in the structure has many benefits, such as low gas loss to the outside, the potential for using in situ gases for pressure maintenance, lowers the need for supplied make-up gases, reduces heat loss, reduced structural stress, and facilitates easier shipping and deployment.

Structural geometry is an important consideration when designing an environmental container. Geometry determines the amount of surface area of the structure both inside and out. The surface area will determine three important considerations in design, the total stress, the gas leak rate, and the mass heat transfer. When plants are first propagated, they require little volume to continue growth. As plants mature they need an appropriate volume to match their size (Prince and Bartok, 1978). Different plants require different amounts of volume at maturity. The ideal structure would expand and collapse in accordance with the desired volume needed for plant growth. This change in volume would reduce the required atmospheric gases and increases the efficiency of the system. Geometry also influences the ability for use of ambient light, air circulation, cycling of water/humidity, and access to the plants. The ability to illuminate the plants will be affected by the geometric shape of the structure. If the structure is transparent (Figure 3), then the shape will determine where the light comes from and the degree of attenuation it will have as it passes through the film. If the structure is opaque, then its size can increase and the lights could be mobile within the structure to maximize light usage. The ultimate shape will be determined by the manner in which the structure is deployed. A flexible structure will lend itself to rounded shapes, while rigid-structure will tend to have more flat space (Figure 5). A compromise might use an inflatable expanding foam concept (Figure 4), where in the shape can be inflated to a dome or cylinder and then rigidized into a solid structure. The total surface area of any particular shape will greatly influence the thermal characteristics of the structure. The lower the surface area the lower the heat loss in the structure.

Materials considerations in the building of a greenhouse structure will not be addressed in this paper (see Sandy, 2000) but the requirements for those materials are a consideration for this study. The outside shell material, depending on the path taken (transparent or opaque), will need to withstand the rigors of the Martian atmosphere, including ultra-violet radiation and low temperatures. The inside shell must be able to withstand high humidity, interaction with nutrient solutions, thermal stress, and bio fouling. Internal components must be made of materials that can tolerate any volatile organic compounds associated with plant growth. The biological interactions of materials in the structure must be kept at a minimum so that they remain functional throughout the mission. All of the materials must be able to undergo extreme temperature changes imposed from the transit part of the mission.

One of the best gauges of how effective any part of a space mission is the return from mass delivered into space or equivalent system mass (Drysdale, 1995). Most components of a space mission have no return, other than being required to accomplish the mission, this is not the case when it comes to Advanced Life Science (ALS). The mission of ALS is to generate the necessities of life from on board or in situ materials and then to recycle as much of that as is possible. This can reduce the mass required to launch and give a potential return on investment. There is no such thing as a closed loop system, which means that there will always be some required input and some loss from the system. The Mars Greenhouse Project is an attempt to maximize the utilization of plants for life support at the lowest mass required.

Methods and Materials

In an effort to define low pressure limits for plant production systems, a series of tests was initiated to define humidity sensing and control capabilities, heat rejection issues associated with electrical lighting, dissolved oxygen (DO) in nutrient solutions, and plant transpiration responses. Tests were carried out in a vacuum chamber located at KSC (Thermotron, Figure 1). This chamber is ~1.22m x 1.22m x 2.4m giving a volume of ~3.57m^3 which does not account for reduced volume from mechanics and instrumentation. It is capable of going to a low pressure of less than 1 mm Hg with thermal control of about a 1KW heat load. At low pressure, the ability to remove heat is greatly diminished.

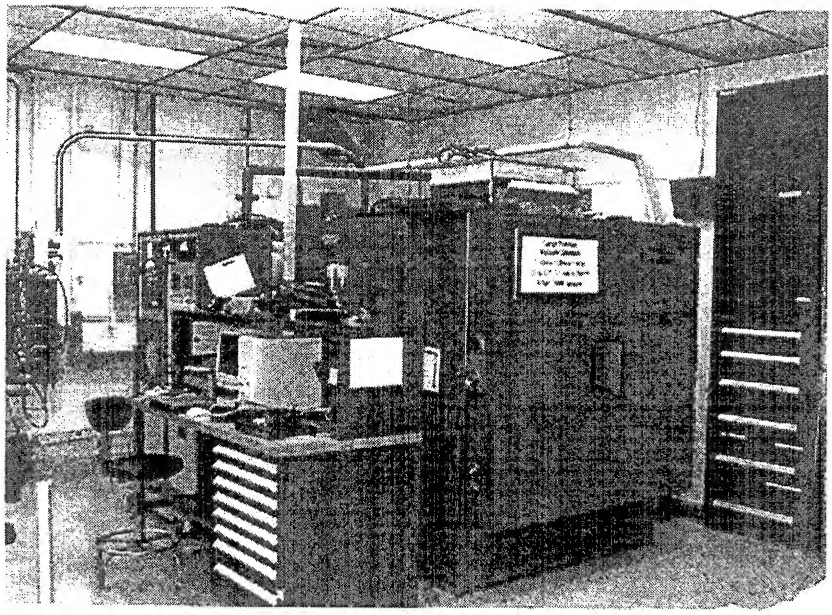

Figure 1 Thermotron test chamber

To support plant testing, a light test stand consisting of three 400 W high-pressure sodium (HPS) lamps was assembled. The removal of the heat from the lamps was handled efficiently by the Thermotron cooling system, but as the air was cooled, the moisture condensed, thus reducing the humidity. In order to maintain humidity in the system two impeller type humidifiers were added. This addition of moisture to the system helped to achieve a relative humidity (RH) of >75% at low pressures ≤ 20 kPa but were insufficient to maintain 75% RH at 10 kPa. Maintaining humidity control was critical to assessing plant transpiration rates at low pressure. These tests did show that plants could survive at low pressure. For a more in depth description and results (see Corey et al. 2000). These early tests concluded that some means of heat removal would be required to continue test in the Thermotron. To address this problem, two approaches were pursued: addition of two more humidifiers, and incorporating a water barrier for the removal of the excess heat. The addition of more humidifiers did maintain a higher humidity but created large amounts of water condensing to the chamber floor. We then designed a water barrier to be place under the lamps to aid in the removal of heat. This barrier consisted of three sheets of acrylic plastic, a 25 mm middle core, with cutouts to allow for water, and two outer 3 mm sheets to contain the water. The barrier had one inlet and one outlet. The first static test on the barrier leaked at 14 kPa. The barrier was then reinforced with angle aluminum and 3 mm through bolts and tested again. This time it did not leak but burst at about 27 kPa. This then lead to version three, which used 6 mm polycarbonate, sheets as an outer skin. The next test obtained about 103 kPa before shearing one of the through bolts. Next version used 6 mm bolts and was tested again. When pressured to the maximum expected pressure (137 kPa) there was a small amount of leakage but the outside skin distended approximately 25 mm from the flat plane (Figure 2). This distention shows how a small amount of pressure can cause large amount of stress.

It is estimated that over 17000 N of force was exerted on each panel. This testing was for the worst case scenario and although the barrier may have worked, we have since been delivered a water jacket enclosed HPS lamp (250 W) designed by Phil Sadler (Sadler Machine Co. Tempe, AZ). We tested the lamp with its surrounding water jacket and found it satisfactory at worst-case pressures expected. Based on this preliminary test, we plan to replace the three 400 W HPS lamps with three water-cooled lamps. Assuming that about 70% of the lamps output is long wave radiation and that most of the long wave radiation from these lamps can be removed by the water jackets, this should remove 400 W x 0.7 x 3 = 840 W of the added heat. The water is circulated through an access plate and cooled outside the chamber thus removing the heat.

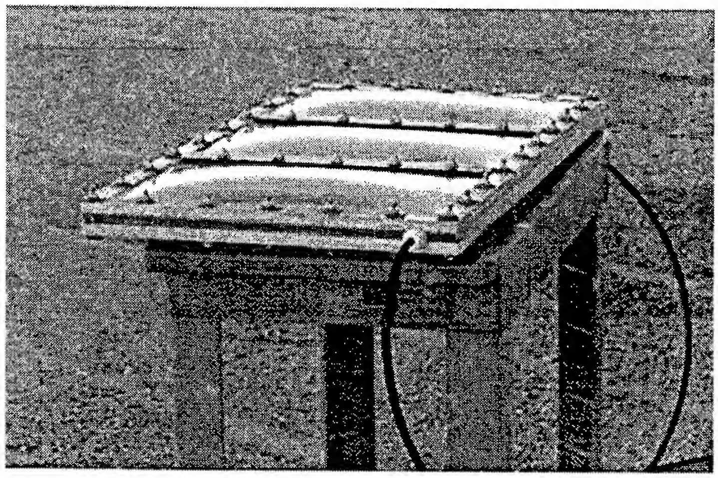

Figure 2 Water barrier test.

One of the unknowns when we started the project was whether the instrumentation would work at low pressure. Certain types of instruments are unaffected by low pressure such as thermocouples and pressure sensors, while others such as humidity sensors, dissolved oxygen (DO) probes, or pH could be sensitive. We tested various types of humidity sensors to determine their capabilities at different pressures. The instruments tested were: Vaisala HMI 41 Humidity and temperature indicator (capacitance type), Edgetech Vigilant hygrometer (chilled mirror type), LI-COR 6252 (infrared type), and the basic wet/dry bulb type systems. The test consisted of taking the instruments down in pressure and reading their outputs. This information was logged and plotted as shown in Figure 6, showing the variation in readings from the different instruments. All of the tracked closely with each other except the infrared detector, which tended to be slightly lower at lower pressures. We suspect the infrared detector was not given enough time to equilibrate to the conditions. From this test, we can conclude that pressure did not adversely affect the ability of the sensors to detect humidity levels. When final design of the control system is considered the selection will be either the wet/dry bulb sensor or the Vaisala sensor, other criteria such as maintenance may be primary factors deciding the ultimate selection.

An important factor in the growth of plants is the amount of DO present in the root zone. In a reduced pressure atmosphere, the DO in soils or nutrient solutions should be related to the partial pressure of oxygen. For many crops, DO levels need to be kept at ~3ppm(mg/l) or greater to achieve optimal growth. A YSI model 51B oxygen meter was tested to determine its capabilities at low pressure. The experiment consisted of the probe being placed in a container of water inside the vacuum chamber. The pressure was lowered and the water was allowed to equilibrate and readings were taken. These readings were then plotted and compared against the theoretical predictive values (Figure 7). This test showed that the instrument was unaffected by the reduced pressure, which suggests that this type of probe should be useful for low-pressure greenhouses.

Using the vacuum chamber for low-pressure test has certain challenges when trying to get the data. Quite often only sensors from instruments are place in extreme environments and the data is then relayed via electrical lines outside. When operating a system on Mars it is apparent that all of the sensing system will have to operate at the Mars ambient conditions. We have chosen to put all of the instrumentation in the environment that it will have to operate. The fact that the experiment is at a different pressure means that some interface must be done to bring data from a low-pressure level to a high-pressure level. Initially the readings were taken by directly reading the instruments through a window in the chamber. This system did not work, as quite often when pressure changes were made the window would mist over preventing readings. The chamber has now been outfitted with an internal network that allows instruments to be connected on this network to get the data out. All of the instruments selected have a RS232 protocol output. This protocol does not allow multiple units on the same network. To solve this problem RS232 to RS485 converters are used. The RS485 protocol is a current sensing system that can then be multiplexed onto a multi-drop 3-wire system. Each 232/485 converter has an address that is unique. This gives the ability to communicate with each instrument individually and log the data outside the chamber. Some of the instruments are able to operate independently which then leads to a distributive type system. Should any of the instruments fail this will not stop the other instruments from reporting their data. A central computer is responsible for communicating with each data and then logging the data.

Results and Discussion

These early tests have shown the difficulty in conducting low-pressure plant test. Although the Thermotron chamber can supply some of the data required to gain knowledge in low-pressure studies, it is not the ideal test bed. Further testing will be conducted in this chamber with adaptations being made as necessary. Upgrades to the lighting system are underway and when completed should help resolve the humidity control situation. At present only short-term test have been conducted. Long term tests are needed with better monitoring and control. A dedicated low-pressure plant growth chamber is needed to conduct long term test. The system needs to be automated for maximum data collection. A CO_2 controlled injection system is required to conduct certain photosynthesis test. The project needs a series of models to be developed which include heat transfer models, Mars ambient light supply model, plant growth at extreme conditions model, power usage model with respect to lighting and heating, deployment schemes, materials models, and others.

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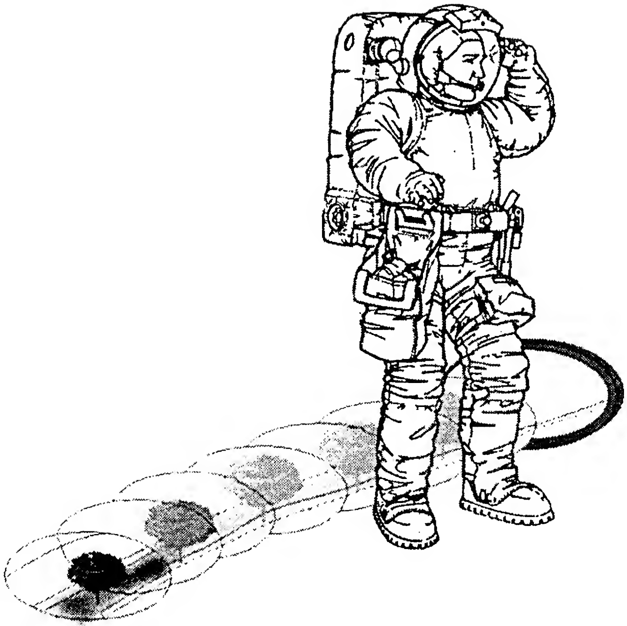

Figure 3 Clear expanding tube on Mars

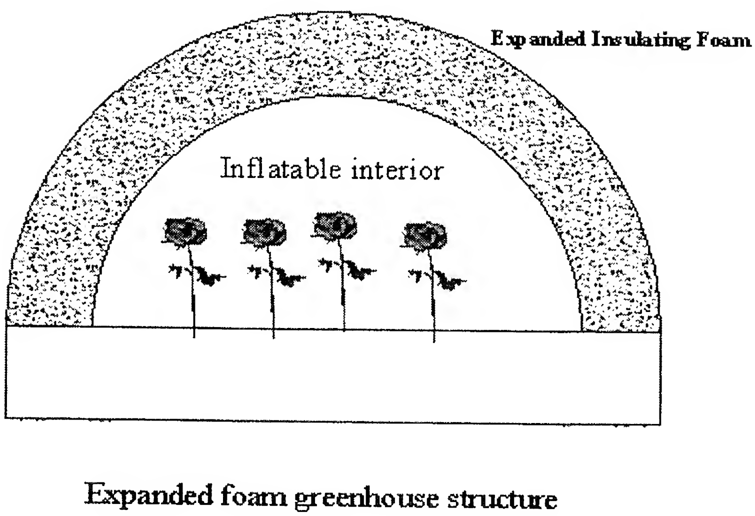

Figure 4 Expanding foam rigid structure

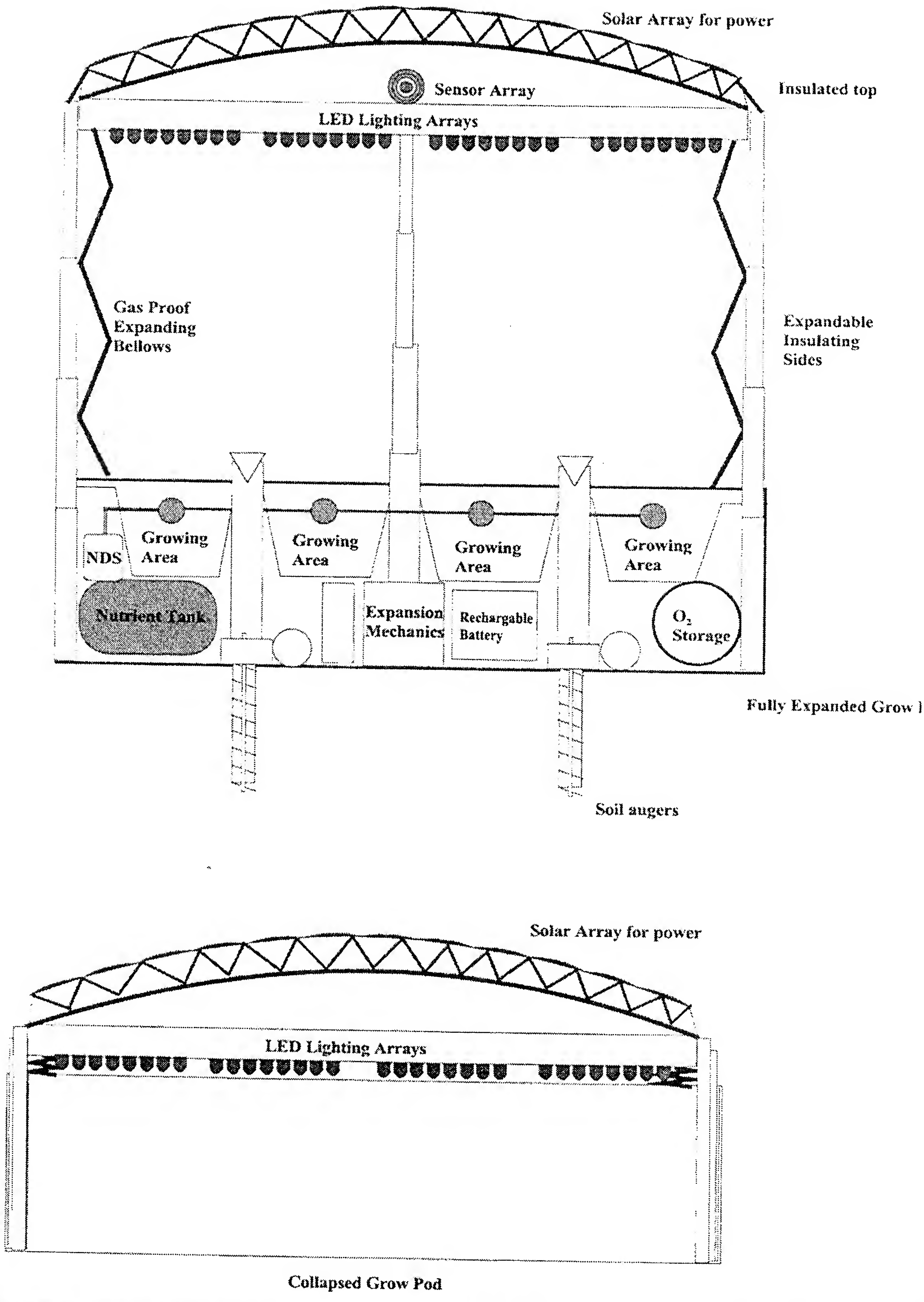

Figure 5 Rigid expanding structure

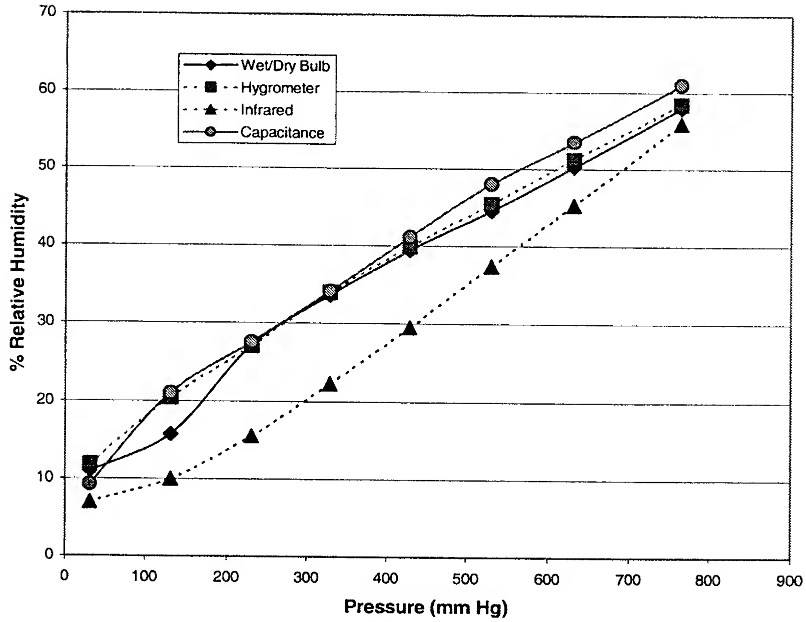

Figure 6. Comparison of humidity sensors at different atmospheric pressures.

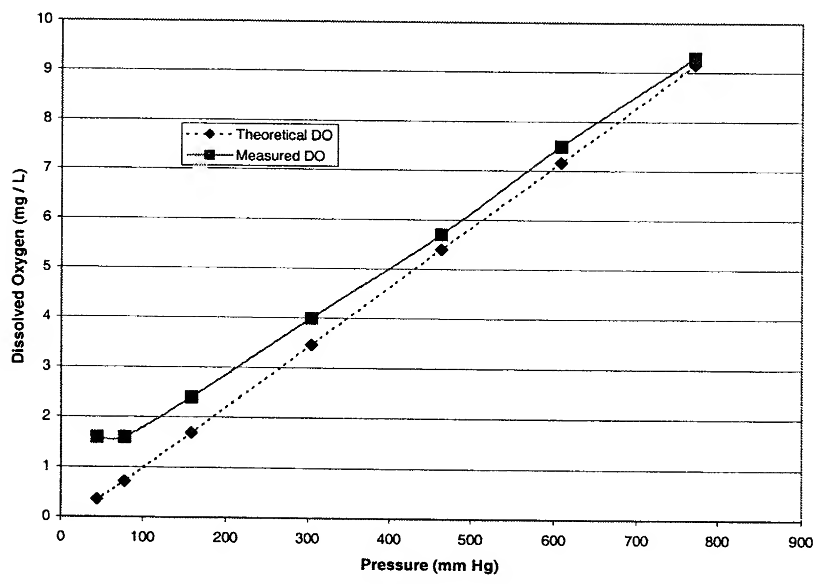

Figure 7. Dissolved oxygen (DO) vs. atmospheric pressure (21% O_2).